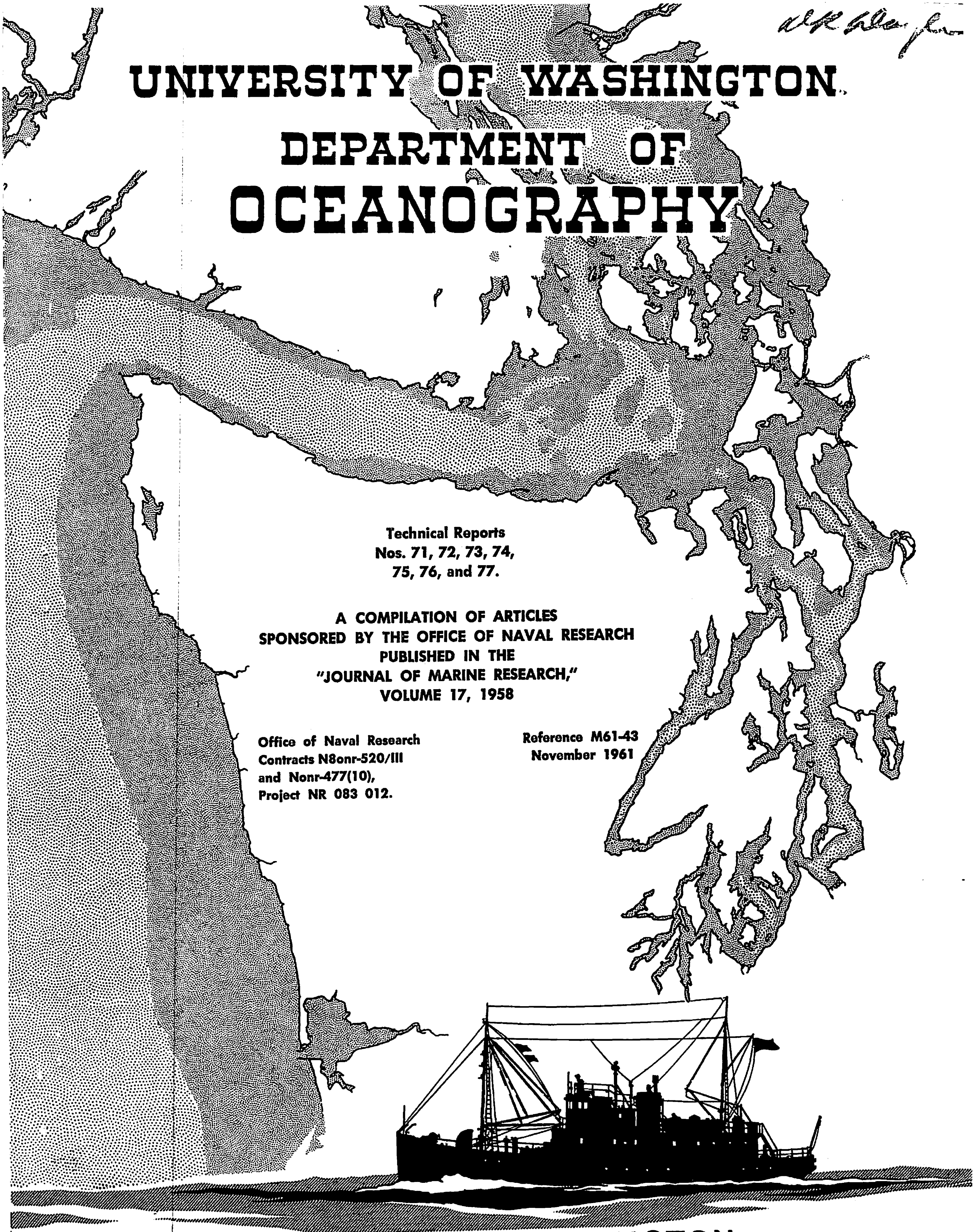

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RHFleming

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Executive Officer

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NOTES CONCERNING THE HALOCLINE IN THE NORTHEASTERN PACIFIC OCEAN[1]

By

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ABSTRACT

The quasi-isothermal halocline between depths of about 100 and 200 m is a striking feature of the temperature-salinity characteristics in the northeastern Pacific, north of about 40° N. An hypothesis is offered to explain the origin of this feature in terms of circulation, dilution, and winter mixing.

INTRODUCTION

Over extensive areas in the northeastern Pacific Ocean, north of about 40° N, the vertical distributions of temperature and salinity are characterized by a quasi-isothermal halocline. Although this halocline is limited to depths of less than 250 m and although temperatures and salinity ranges are variable in different parts of the region, the halocline is a striking feature of the temperature-salinity diagrams. Investigations by Professor T. G. Thompson and his students (Goodman and Thompson, 1940) were among the first to demonstrate the major features of the water masses in the northeastern Pacific. The most recent summary of the thermohaline relationships and of the geographic range of the halocline is by Dodimead (1958).

It is the purpose of this paper to present an hypothesis concerning the processes that contribute to the formation of the halocline in parts of the northeastern Pacific. Although the discussion is limited to this particular feature and area, it is believed that the principles are of broad application to an analysis and understanding of the processes that affect the distribution of properties in shallower depths of the oceans.

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[1] Contribution No. *226* from the Department of Oceanography of the University of Washington. Publication was supported in part by the Agnes H. Anderson Fund of the University of Washington.

OBSERVED CONDITIONS

Characteristic vertical distributions of temperature and salinity during the summer months in the northeastern Pacific (approximately 45° N) are shown in Fig. 1. In the surface layer, usually between 75 and 100 m thick, there is a small increase in salinity and a relatively large decrease in temperature; however, in the halocline below it, usually between 75 and 150 m thick in the whole area, the temperature is relatively constant while the salinity increases rapidly with depth, this salinity increase usually being greater than $1\ {}^{0}/_{00}$. Despite temperature and salinity variations from place to place, it is characteristic of the region that the salinity at the base of the halocline is always nearly $33.8\ {}^{0}/_{00}$. This feature has been discussed by Tully (1953), by Tully and Dodimead (1957), and by Dodimead (1958). These authors recognized the importance of the halocline and have described methods for estimating the salinity at its base (their *index salinity*); furthermore, by assuming that the upper zone (see Fig. 1) results from dilution of water of

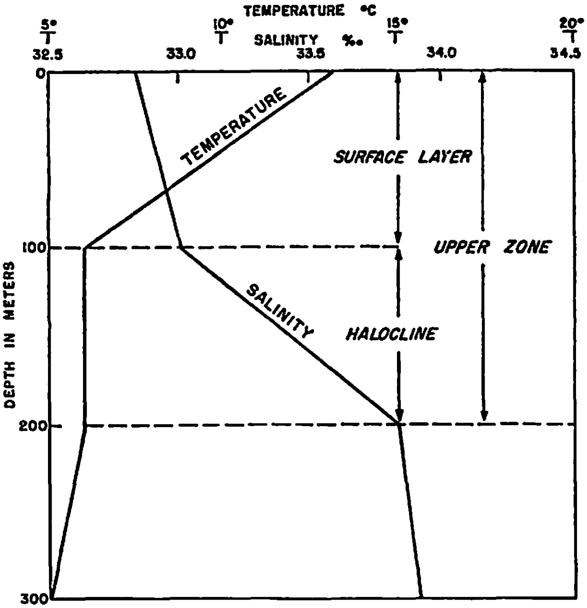

Figure 1. Schematic distributions of temperature and salinity at about 45° N, and terminology applied to features in the upper zone. All values approximate.

about 33.8 $^0/_{00}$ salinity, they have computed the accumulation of fresh water. This "depth of fresh water in the upper zone" has been used by Tully and Dodimead to draw certain conclusions concerning the speed of surface circulation in the northeastern Pacific. Because the halocline is a layer of high stability (rapid increase of density with depth), it seems reasonable to assume that conditions altering the density in the surface layer and in the upper part of the halocline will not affect waters below this. Observations in the area during the stormy winter months (Dodimead, 1958) support this conclusion, for they show not only a well-mixed surface layer with uniform temperatures close to those in the halocline but conditions in the deeper parts of the halocline similar to those found during the summer.

Examination of available T-S diagrams for an area extending from 180° W to the North American continent and from 40° N to the coast of Alaska and the Aleutian Islands showed that the halocline is present over almost the entire area. The following generalizations may be made about the regional characteristics of the upper zone:

1. The salinity at the base of the halocline is about 33.8 $^0/_{00}$ but tends to be greater than this near the American coast.
2. The average salinity in the surface layer (above the halocline) is greatest in the south, where the water characteristics approach those of the Central Water mass, and decreases northward and eastward.
3. Temperatures in the halocline, approximately 10° C in the south (about 40° N), decrease in midocean with increasing latitude, being slightly less than 4° C at about 50° N and over a wide area south of the Aleutians and the Gulf of Alaska. North of about 45° N, on approaching land, the halocline temperatures become warmer than in midocean. South of 45° N the halocline temperatures are cooler than those offshore.
4. Temperatures in the halocline are more nearly uniform in midocean than in coastal waters. To the north, temperatures at the base of the surface layer or in the upper part of the halocline are commonly about 1° C lower than those in the deeper part of the halocline. In the southeast, the upper portions of the halocline are warmer than the deeper portions.

Some of the major features of the geographic variations of the halocline are shown in the schematic T-S curves in Figs. 2A and 2B.

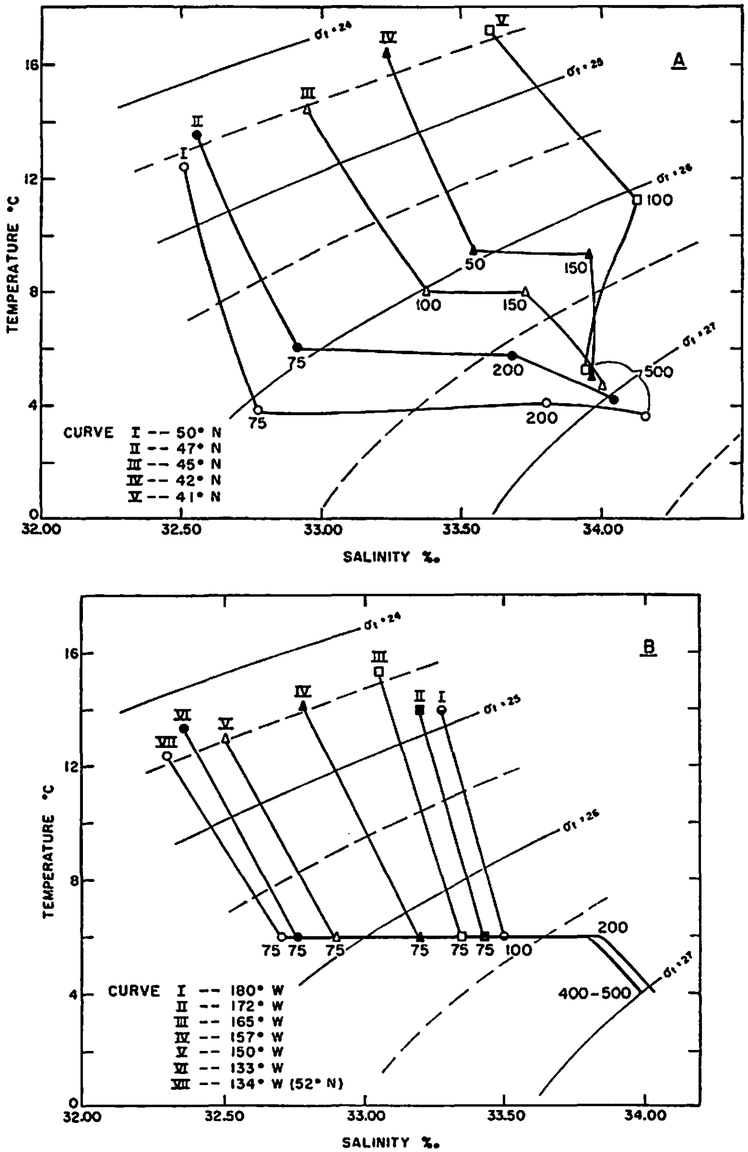

Figure 2. *A*. Generalized T-S relationships at about 155° W extending from 50° N (Curve I) to 41° N (Curve V). Depths in meters are indicated. *B*. Generalized T-S relationships extending from 180° to 133° W along approximately 45° to 47° N, except Curve VII which is in 52° N. Depths in meters are indicated.

Fig. 2A, based on observations made during summer months at about 155° W, represents the relationships at various latitudes extending from 41° to 50° N. These curves are representative of changes in the upper zone with latitude in midocean. Fig. 2B illustrates the way in which the characteristics change from west to east. These curves are based on summer observations at stations where halocline temperatures are about 6° C. Moving eastward from 180° W, the most notable feature is the progressive decrease in salinities in the upper part of the halocline and in the surface layer. The fact that salinities in the surface layer increase with depth indicates that dilution must occur during the summer as well as during the winter. These idealized curves are not representative of the modified T-S relationships near land. Curve I in Fig. 2A shows the temperature inversion in the upper part of the halocline that is typical of conditions over a large area in the higher latitudes. These deviations will be discussed later.

THE PROBLEM

The halocline is a conspicuous and permanent feature in the northeastern Pacific and, allowing for annual changes in the surface layer, is present throughout the year. The fact that both temperature and salinity characteristics in midocean vary with latitude but are relatively uniform for long distances from west to east suggests that the structure is in some way associated with the prevailing current systems. Most of the region under consideration lies between the Sub-Arctic Water mass and the Central Water masses (Sverdrup, *et al.*, 1942). It is tempting, therefore, to postulate that the variable T-S relationships in this region can be explained in terms of lateral mixing on surfaces of equal density. However, it is most unlikely that such processes would produce a layer of uniform temperature and varying salinity. Tully and Dodimead recognized that the region is one of net dilution (*i. e.*, where precipitation exceeds evaporation), and from calculations of the "thickness of the fresh water layer" and from the annual excess of precipitation, they estimated the "age" of the water in the upper zone. However, they did not offer any explanation of the processes that lead to the development of the halocline with uniform temperatures. Therefore, the problem at hand is to develop a model of the system in which a combination of various processes would produce this feature. The following hypothesis, consistent with the known magnitudes of the processes and with the water movements in the region, is offered as a preliminary step in the development of our understanding of northeastern Pacific waters.

THE HYPOTHESIS

Two major premises must be recognized: (1) that the region is one of net dilution; and (2) that winter temperatures in the surface layers are almost identical with year-round temperatures in the halocline. It is therefore possible to account for the development of uniform temperatures in the halocline if the water in the upper zone follows trajectories corresponding to isotherms that represent the geographic features of the halocline temperatures. As the waters move along such trajectories, surface dilution and winter mixing would progressively increase the range of salinity in the halocline as the surface layer became more dilute.

The hypothesis as stated above makes no implicit statement about the direction in which the water must move along the isotherms. If the rate of addition of fresh water is known, it should be possible to deduce from salinities in the surface layer the direction and speed of the water movements. However, as will be shown later, this assumption is not strictly true.

Because of the relatively large vertical spacings of temperature and salinity observations in the halocline, it is often difficult to establish the depth limits and true structure of the layer. Consequently, selection of the halocline temperature from T-S curves is often highly subjective, although the uncertainty is generally less than 1° C. In order to avoid this difficulty, temperatures for the depth at which the salinity was 33.77 $^0/_{00}$ were read off for each station examined. This particular value of salinity was selected because of the previous studies by Tully and Dodimead (1957); also, the temperatures can easily be determined when T-S diagrams are available. These temperatures, then, represent conditions in the deeper portions of the halocline.

The temperature values based on approximately 160 stations were used to prepare Fig. 3[2], which actually represents temperature distribution at salinity 33.77 $^0/_{00}$, but the figure will be used to describe temperatures in the halocline. Although the topography of

[2] Based on Lambert's Azimuthal Equal-Area projection prepared by Scripps Institution of Oceanography.

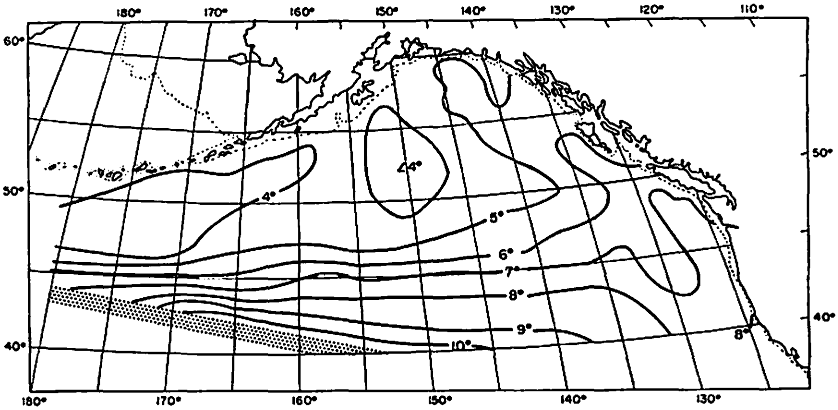

Figure 3. Temperatures in the lower part of the halocline (°C). Data actually represent temperatures on the surface of salinity 33.77 $^0/_{00}$; for summer of 1956, except west of 157° W where data for both 1955 and 1956 were used. Dashed line indicates 100-fathom contour.

the isohaline surface is not shown, in most areas it is at approximately 200 m, with extremes of 100 and 250 m. South of the stippled boundary in the southwestern portion of Fig. 3, salinities exceed 33.77 $^0/_{00}$ at all depths, and near the boundary the halocline is not always present. The data used to prepare Fig. 3 were collected during the summer of 1956 by the Pacific Oceanographic Group (Fisheries Research Board of Canada, 1957) and by the University of Washington (Love, 1957); to the west of 157° W, observations made by the Pacific Oceanic Fisheries Investigations in the summer of 1955 were also used (McGary, *et al.*, 1956).

If the previously stated hypothesis is correct, then the isotherms in Fig. 3 should parallel the trajectories of the waters in the halocline. In midocean these isotherms are relatively closely spaced, but toward the east they spread apart. The 7° C isotherm is close to the parallel of 45° N to a distance of about 750 km from the continental coast, where abrupt changes in the trends of the isotherms indicate tongue-like penetrations roughly parallel to the coast, with the 5° and 6° isotherms extending northward and the 7° and 8° isotherms extending southward. The lowest temperatures, less than 4° C, are present to the south of the Gulf of Alaska and in an east-west band south of the Aleutians. Temperatures somewhat higher than 4° C are found near the coast in the Gulf of Alaska and near the Aleutian Islands.

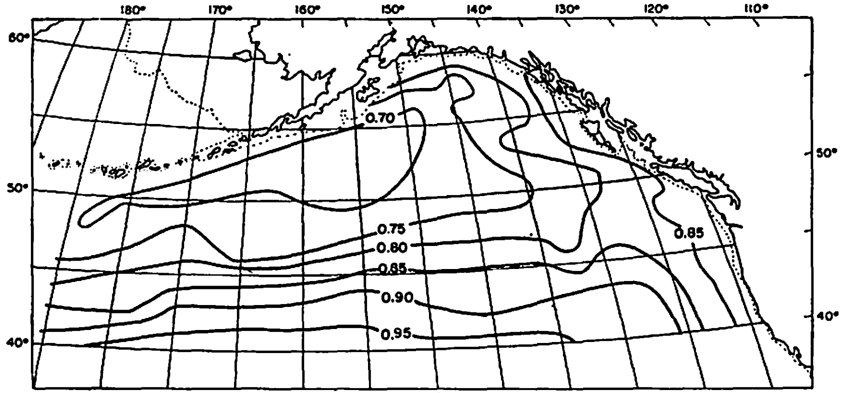

Figure 4. Dynamic topography of the 200-decibar surface relative to 1000 decibars (dynamic meters); for summer of 1956, except west of 157° W where data for both 1955 and 1956 were used.

In order to determine the directions and speeds of circulation in the halocline, Fig. 4 was prepared with data from the same stations as those used in Fig. 3. Fig. 4 shows the topography of the 200-decibar surface relative to 1000 decibars. The parallelism between the isotherms in Fig. 3 and the contours of dynamic topography in Fig. 4 is obvious and thus supports the hypothesis that trajectories of water in the halocline are parallel to isotherms of the halocline temperatures.

In midocean the flow is generally from west to east, but the dynamic isobaths diverge at a distance of about 750 km from the coast, the "split" occurring at about 45° N with flows north and south. The northward flow into the Gulf of Alaska tends to follow the Gulf coast and to extend westward close to the Aleutian Islands. The southward flow occurs off the coasts of Washington and Oregon, but about 400 km off the coast there is a trough in the dynamic topography, with northward flow near the coast. This is consistent with the presence of warmer water near the coast in the southeastern part of the area.

The speeds of circulation indicated in Fig. 4 are relatively small. In the midocean area the speeds are about 3 km/day, decreasing to less than 2 km/day towards the east and in the Gulf of Alaska. The cold waters in the north (halocline temperatures $< 4°$ C) have a sluggish circulation with speeds of less than 1 km/day. Since distances along the isotherms in Fig. 3 are of the order of several thousand kilometers, it would require about three years for water in the halocline to travel from 180° to 135° W, and probably an equal amount of time to flow northward and then westward along the Aleutian Islands.

The parallelism between the halocline temperatures and the dynamic topography of the 200-decibar surface is strong evidence in support of the hypothesis because there is no *a priori* reason to expect such a relationship between temperatures on an isohaline surface and distribution of mass at greater depths. There are two further consequences of the hypothesis: winter temperatures in the surface layer should correspond to the halocline temperatures; and the progressive dilution that can be computed from salinity in the upper zone should be in agreement with the speed of movement and with the geographic pattern of the excess of precipitation over evaporation.

Because of probable year-to-year variations in climatic conditions in the region under consideration, too much confidence cannot be placed in a comparison of data from an individual year with climatic averages based on many years of observations. Comparison of Fig. 3 with the February and March data included in Robinson's (1957) excellent study of temperatures in the northeastern Pacific showed that north of about 45° N in midocean the temperatures in Fig. 3 were within 1° C of those in the surface layer in winter. In the Gulf of Alaska and westward, surface temperatures were generally cooler, in some places by as much as 2° C. South of about 45° N the surface temperatures were higher, the difference increasing to 3° or more at about 40° N in the area of southward flow off the California coast. Rather than indicating disagreement with the hypothesis, these results are consistent with observed conditions. The water flowing northward into the Gulf of Alaska is entering higher latitudes, and it should be anticipated that winter temperatures will be colder than the halocline temperatures. Dodimead (1958) has prepared a diagram that shows temperature inversions of 0.5° to 2° C in the halocline in the area north of 50° N. The water turning southward is obviously entering latitudes with higher winter temperatures, hence waters in the upper part of the halocline and in the surface layer would be expected to be warmer.

The surplus of precipitation over evaporation, shown in Fig. 5, is based on estimates of Jacobs (1951). It is seen that essentially

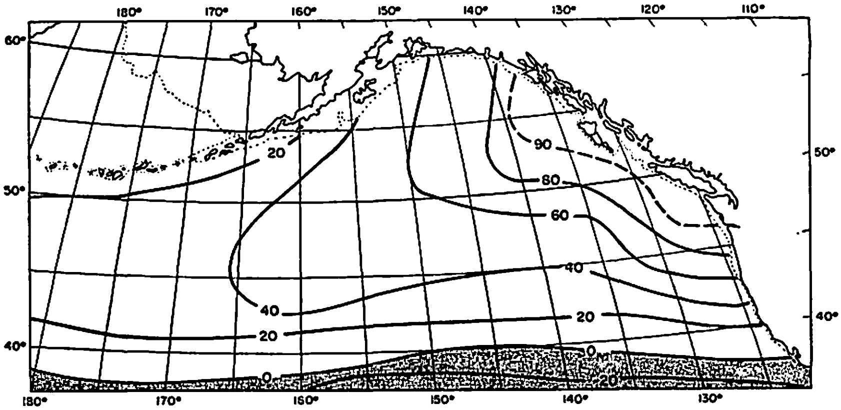

Figure 5. Mean annual values of the surplus of precipitation over evaporation (centimeters/year). Shaded areas indicate a deficit in precipitation. (After Jacobs, 1951).

the entire area under consideration is one of net dilution, the surplus of precipitation being least in the west and south and increasing to a maximum of more than 90 cm/year off the coast of British Columbia and southeastern Alaska. As waters of the upper zone move eastward they enter regions of greater surplus of precipitation, therefore the annual rate of accumulation of fresh water should increase as the water approaches the coast. Attempts to use the "thickness of the freshwater layer" and the speed and direction of flow along the halocline isotherms to compute the annual addition of fresh water have shown agreement with Fig. 5 to within a factor of two or three. This may reflect the fact that the data in Fig. 5 are not correct, but it is believed that this simple approach is not valid because: (1) movements of the surface layers are not parallel to the dynamic isobaths shown in Fig. 4; and (2) convergence and divergence occur in the surface layer. It is beyond the scope of this paper to discuss these aspects in the detail they deserve. Charts of dynamic topography of the surface relative to 1000 decibars (Dodimead, 1958) compared to Fig. 4 show differences in flow, and charts of the fresh water layer in the same report support the thesis of divergence and convergence. Note that the excess of precipitation over evaporation approaches zero in the vicinity of the boundary in the southwestern portion of Fig. 3 and that, to the south, there is a net loss of water. It is believed, therefore, that the eastward moving waters south of about 40° N are modified by processes of evaporation and winter mixing and that the location and character of the oceanographic boundary region, referred to by Dodimead (1958) as the Polar Front, are largely the consequences of flow patterns and of the relation of evaporation and precipitation.

As indicated previously, it is the purpose of this paper to present a simple hypothesis concerning the processes that control temperature and salinity relationships in the upper zone in the northeastern Pacific, and it has been pointed out that a detailed analysis would require a more careful evaluation of the movements and processes affecting the surface layer. Several other factors must also be taken into account regarding water near the coast. These are:

1. Intrusion of coastal water from the south. This water has a different T-S relationship than offshore water, and, as the two masses are mixed, the southern water modifies the simple model described here.
2. Divergence (or upwelling) along the coast, at least as far north as Vancouver Island. This upwelling is not obvious at the surface because of the development during summer months of a thin surface layer of dilute water that is largely a result of river runoff. However, the surface layer is generally thin and the halocline, if present at all, is at shallow depths and is also thin.
3. River runoff that adds relatively large amounts of fresh water to inshore waters as they move northward and around the Gulf of Alaska.
4. Mixing processes in inshore waters. The strong tidal currents characteristic of coastal waters in the area under consideration must, in the embayments and over the Continental Shelf, contribute to vertical mixing in the surface zone. Consequently, the features of the upper zone that have been described in this paper will tend to be modified, particularly in northern areas where winter cooling and the formation of sea ice may produce water of sufficient density to sink to moderate depths. The relatively cold waters in the halocline in the area south and west of the Gulf of Alaska are believed to be produced in this way.

Although listed separately, these four modifying processes operate simultaneously, and they must be taken into account in more detailed studies of the water characteristics within several hundred kilometers of the coast. In midocean, the thermohaline structure of the upper zone is clear-cut and uniform over long distances where water movements are in an eastward direction. The barrier formed by the American continent forces these waters to turn north and south as they approach land, and this in itself will lead to unstable flow patterns that favor lateral mixing. Intermixture of oceanic waters will tend to destroy the isothermal character of the halocline, and as these mix with coastal waters there will be further transformations. It seems reasonable, therefore, to consider the areas lying within several hundred kilometers off the coast as regions in which the thermohaline structure of the upper zone will be variable in both space and time.

DISCUSSION

In an earlier study (Fleming, 1955) an attempt was made to designate the natural regions of the northern Pacific Ocean. Since relatively few data were then available, it is now desirable to redefine the boundaries of such regions in the northeastern Pacific. Fig. 6 shows the principal areas under discussion. The largest is that designated as the Subarctic Transition, in which conditions are relatively uniform along the trajectories but in which the temperature and salinity characteristics change rapidly when crossing the current. In the southeast, water is introduced from the south by the Southern Intrusion, whose waters are modified by coastal processes and by mixing with offshore waters in the Mixing Area. South of about 45° the mixed waters are carried away to the south, but north of 45° the products of this mixing, further modified by coastal processes and by admixture with waters from the Subarctic Transition, contribute to the general westward flow in the Alaskan Coastal area. The large area of relatively uniform conditions and sluggish circulation lying between the Alaskan Coastal area and the Subarctic Transition has been designated as the Alaskan Gyral. Since the boundaries between the areas (see Fig. 6) may vary in position from year to year and possibly during a year, they should be considered as only approximate and should be defined in terms of the circulation and of the thermohaline characteristics in the upper zone. The chief reason for designating these natural areas is to simplify discussion of certain problems such as the zoogeography of the region.

The hypothesis developed in this paper provides a rational basis for zoogeographic studies of plankton and smaller nekton that spend a major part of their existence at depths in or below the halocline.

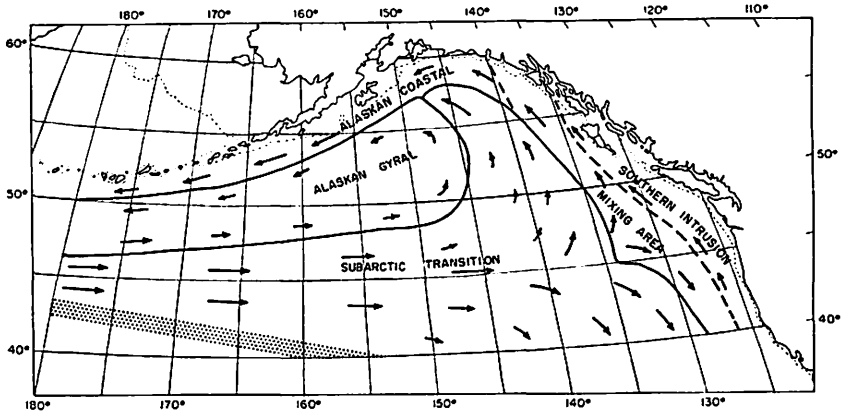

Figure 6. Natural areas in the northeastern Pacific based on the circulation and on the thermohaline characteristics in the upper 200 m. Arrows show the general pattern of flow at about 200 m.

In the Subarctic Transition the effects of lateral mixing appear to be small, therefore organisms will tend to be carried with the water in the trajectories that parallel the halocline temperatures (Fig. 3) or the dynamic isobaths (Fig. 4). It might be expected, therefore, that in the Subarctic Transition the species composition of the larger plankton and smaller nekton should change rapidly normal to the trajectories but should be uniform over long distances along the trajectories. Since water movements in the halocline are relatively slow, it would require several years for a population introduced at 180° W to be carried to the mixing area off the continental coast.

The Southern Intrusion should be expected to introduce its own characteristic population that will either disappear gradually or, if the organisms tolerate the modified conditions in the Mixing Area, be carried away to the south or to the north after admixture with forms originally present in the Transition area. The Alaskan Coastal area should have a mixed and probably variable species composition containing forms introduced from shallow inshore waters. The Alaskan Gyral should be characterized by its own homogeneous population.

This approach to a study of zoogeography, based primarily on the pattern of circulation at a depth of about 200 m, indicates the value of relating the regional distribution of organisms to the T-S relationships in the upper parts of the water column. Such a procedure has been used by Haffner (1952).

Although temperature may be an important environmental feature for plankton and nekton, it is difficult to decide what temperatures should be selected for those forms that undergo diurnal vertical migrations. Particularly during summer months, there may be large temperature differences between the surface and depths of several hundred meters. It seems more rational to consider that the major features of zoogeography of the plankton and nekton are related to the pattern of circulation. If, as in the northeastern Pacific, there is a relationship between circulation pattern and temperature in the halocline and, in general, with winter surface temperatures, a coincidental correlation of these temperatures with the zoogeographic features might be expected.

It is obvious that the concepts presented in this paper should be tested more thoroughly. The study should be extended to the west and to the southeast to obtain a more complete picture of the characteristics of the halocline and of the processes that produce it. As mentioned earlier, more detailed studies should also be made of the convergence and divergence in the surface layer. It is essential that field measurements be made to determine more precisely the structure of the halocline. These measurements should not be limited to temperature and salinity but should include dissolved oxygen and possibly other properties such as inorganic phosphate and the other biologically-affected substances. It is usually possible from the observed properties to determine the depth of mixing and the characteristics associated with the water produced during the previous winter. If, as stipulated by the hypothesis, the halocline is the result of a number of years of progressive dilution, then some evidence of the water produced in previous winters should be obtained from such detailed studies. It is possible that the gradient of salinity in the halocline (and the same is probably true for dissolved oxygen) is not uniform but is actually of a stair-step structure, the "risers" corresponding to the water produced each winter and the "treads" to the progressive annual dilution.

SUMMARY

1. The thermohaline structure of the northeastern Pacific (north of about 40° N) is characterized by a quasi-isothermal halocline about 100 m thick and located below a surface layer about 100 m thick.

2. In midocean the temperature in the halocline increases from about 4° C at 50° N to 10° C at about 40° N. From west to east, temperatures are uniform to within about 750 km of the coast, where the isotherms tend to parallel the coast.
3. The dynamic topography of the 200-decibar surface relative to 1000 decibars indicates flow in the halocline parallel to the isotherms of the halocline temperatures.
4. According to the proposed hypothesis, the halocline is formed by progressive dilution over a period of several years, the water moves along trajectories parallel to the halocline isotherms, and each winter the mixing produces a surface layer where the temperature is that of the halocline and where the salinity is lower than that of the deep part of the halocline. Where the flow has a north-south component, temperatures in the halocline are not uniform.
5. The persistence of the halocline structure in the Subarctic Transition implies that lateral mixing is of negligible importance as a modifying process in the upper 200 m.
6. On the basis of thermohaline characteristics in the upper zone, of the pattern of circulation, and of the hypothesis concerning the life history of the waters, certain natural regions are designated that may provide the basis for zoogeographic studies.

ACKNOWLEDGMENTS

This token of my respect and affection is presented as a tribute to my distinguished colleague Professor Thomas Gordon Thompson on his seventieth birthday.

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